

# KNOCKING DETECTION APPARATUS AND DETECTION METHOD

## BACKGROUND OF THE INVENTION

### Field of the Invention

The present invention relates to a knocking detection apparatus and detection method that detect, with high precision, the presence of knocking and the occurrence timing thereof from changes in ion currents that are detected using spark plugs at the time of combustion of an internal combustion engine.

### Description of the Related Art

It is known that ions are generated when fuel is combusted inside the cylinders of an internal combustion engine and that these ions can be measured as ion currents by disposing probes that apply a high voltage inside of the cylinders. Because knocking vibration components are superposed on the ion currents when knocking occurs in an internal combustion engine, the occurrence of knocking can be detected by detecting these vibration components. However, in a case where spark noise including many frequency components is superposed on the ion currents, this ends up being detected as vibration components of the knocking and is mistakenly determined to be knocking even if knocking is not actually occurring.

The following technologies have been disclosed as technologies to avoid this drawback. First, the technology disclosed in Japanese Patent No. 3184451 (pp. 2-3, Figs. 1 and

2) is disposed with a bandpass filter that filters only the knocking frequency components superposed on the ion currents when knocking has occurred and a noise-use bandpass filter that allows frequency components different from the knocking frequency components to pass. For example, by blocking off switching means when noise resulting from the operation of an injector is detected through the noise-use bandpass filter, a knocking signal is not inputted to a determination circuit.

In the technology disclosed in JP-A-11-2175 (pp. 3-4, Figs. 1 and 3), signals based on the ion currents are allowed to pass through a high-pass filter, thereafter knocking signals are allowed to pass through a filter allowing a specific frequency band to pass, only the noise component is separately retrieved by a filter obstructing the specific frequency band, both are respectively peak-held, digitally converted and imported to control means, both signals are compared by the control means, and it is determined whether or not knocking is occurring from the compared signals.

Moreover, technology is disclosed in JP-A-61-57830 (pp. 3-4, Figs. 1 and 3) where signals obtained through a filter selectively allowing knockingsignals to pass from signals based on the ion currents and a filter selectively allowing unique vibration frequencies generated by the mechanical dimensions of each cylinder to pass are respectively integrated over a predetermined period, signals detecting the occurrence of

knocking are obtained from the ratio of the respective integrated values, and the signals are integrated during a predetermined number of revolutions, whereby the determination of knocking is conducted.

Moreover, technology is disclosed in JP-A-11-295188 (pp. 5-8, Figs. 9 to 11) where signals based on the ion currents are passed through a high-pass filter and a low-pass filter, whereby only a knocking detection-use signal is extracted, the knocking detection-use signal is A/D converted, thereafter discrete Fourier transformed, the frequency is analyzed, it is determined from the result of the analysis whether the signal results from knocking or from noise, and the running state of the internal combustion engine is determined.

As described above, these various technologies have been disclosed. However, in the case of Japanese Patent No. 3184451, even if a signal including the knocking component is detected, it is determined to be invalid if a signal including spark noise is included, and it is mistakenly determined that knocking is not occurring even if knocking is occurring. Also, the ion currents are signals that are small depending on the running state, and the noise signal becomes large when the operating noise of the injector and external noise such as phone are superposed, so that knocking cannot be completely detected with the methods of JP-A-11-2175 and JP-A-61-57830.

Also, the prior art uses, as the detection target, time

intervals where the intervals between each ignition are used as units in relation to knocking detection, and cannot accurately detect knocking, which is a phenomenon that appears and disappears in units of time shorter than these. For this reason, there has been the problem that control methods cannot be made to correspond to the timing of knocking occurrence. Moreover, there have been the problems that the resistance of the determination function has been low with respect to ion current signals whose amplitude has been increased due to the influence of additives added to the fuel and the ion currents on which are superposed impulse noise including many frequency components. Also, in all of the prior examples, knocking determination precision has been low because the time resolution has been low.

#### SUMMARY OF THE INVENTION

The present invention has been made in order to solve these problems, and it is an object thereof to detect, with high precision, the occurrence of knocking and the timing thereof with time units narrower than intervals between ignitions, even in a case where the ion currents generated inside the cylinders of an internal combustion engine are measured and noise is superposed on the ion currents.

A knocking detection apparatus pertaining to the invention comprises: spark plugs disposed in cylinders of an

internal combustion engine; ion current detecting means for detecting ion currents flowing in the spark plugs; time-frequency transforming means for setting time intervals allowing one or more overlaps within a time from after ignition by the spark plugs to until its own cylinder or another cylinder next ignites, and sampling current values of the ion currents in the respective time intervals to determine the time-frequency components thereof; knocking detecting means for detecting knocking on the basis of the time-frequency components; and detection control means for inputting a running status and controlling the time-frequency transforming means and the knocking detecting means.

A knocking detection method pertaining to the invention includes: ion current detecting means for detecting ion currents using spark plugs disposed in cylinders of an internal combustion engine; time-frequency transforming means for setting time intervals allowing one or more overlaps within a time from after ignition by the spark plugs to until its own cylinder or another cylinder next ignites, and sampling current values of the ion currents in the respective time intervals to determine the time-frequency components thereof; knocking detecting means for detecting knocking on the basis of the time-frequency components; and detection control means for controlling the time-frequency transforming means and the knocking detecting means, wherein the detection of knocking is conducted by the

detecting control means inputting a running status of the internal combustion engine and controlling the time-frequency transforming means and the knocking detecting means to determine time-frequency components from sampled values of the ion currents.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram showing the schematic configuration of a knocking detection apparatus and detection method according to a first embodiment of the invention;

Fig. 2 is a block diagram describing ion current sampling in the knocking detection apparatus and detection method according to the first embodiment of the invention;

Fig. 3 is an explanatory graph of ion current detection intervals in the knocking detection apparatus and detection method according to the first embodiment of the invention;

Figs. 4A, 4B and 4C are explanatory graphs of time-frequency transformation and knocking determination function values in the knocking detection apparatus and detection method according to the first embodiment of the invention; and

Figs. 5A, 5B and 5C are explanatory graphs of time-frequency transformation and knocking determination function values in a knocking detection apparatus and detection method according to a second embodiment of the invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

### First Embodiment

Figs. 1 to 4C are diagrams describing a knocking detection apparatus and detection method according to a first embodiment of the invention. Fig. 1 is a block diagram showing the schematic configuration of the knocking detection apparatus and detection method, Fig. 2 is a block diagram describing ion current sampling, Fig. 3 is an explanatory graph showing sampled intervals in ion current detection, and Figs. 4A, 4B and 4C are explanatory graphs describing the result of time-frequency transformation of ion currents and knocking determination function values.

In Fig. 1, an ignition device 1 includes a publicly-known ignition circuit, and ion current detecting means 2 detects an ion current from the current of a secondary ignition circuit and is a publicly-known ion current detection circuit. As described later, time-frequency transforming means 3 conducts a Fourier transform so that knocking can be determined from an ion current signal, and knocking detecting means 4 determines the presence of knocking from the result of transformation by the time-frequency transforming means 3 and detects the timing of the knocking.

Detection control means 5 inputs the running status of an internal combustion engine, controls the time-frequency transforming means 3 and the knocking detecting means 4, and

transforms, in accordance with the running status of the internal combustion engine, one or both of sampled times of ion current values resulting from the time-frequency transforming means 3 and an ion current sample number serving as the target of time-frequency transformation. The result of detection by the knocking detecting means 4 is given to ignition control means 6, and the ignition control means 6 conducts control of ignition times in accordance with the state of knocking.

The time-frequency transforming means 3 includes ion current sampling means 7 and ion current sampled value transforming means 8 shown in Fig. 2. The time-frequency transforming means 3 first determines ion current sampled values  $x(0)$ ,  $x(\Delta t)$ ,  $x(2\Delta t)$ , ... from the detected ion currents with respect to  $0$ ,  $\Delta t$ ,  $2\Delta t$ , ... that are times of set intervals from a starting point determined by the detection control means 5. In this embodiment, a case where  $\Delta t = 5\mu$  is used as an example, but  $\Delta t$  can be optionally set depending on the conditions.

Next, the time-frequency transforming means 3 determines the time-frequency components  $C_n(f)$  in the time intervals from the ion current sampled values included in the time intervals  $I_n = (T_n, T_n + \Delta T, \dots, T_n + (M-1)\Delta T)$  that are set allowing overlap determined by the detection control means 5. That is, here, the time-frequency transforming means 3 sets, as shown in Fig. 3, time intervals allowing one or more overlaps in the time from the ignition determined by the detection control means



5 to when its own cylinder or another cylinder ignites, samples the current values of the ion currents with respect to each time interval and determines the time-frequency components thereof. In the present embodiment, an example is described where  $M = 256$  and  $T_{n+1} = T_n + (M/K)\Delta T$  (where  $K = 8$  and  $n = 0, 1, 2, \dots$ ), but the effectiveness of this embodiment is not limited to these values.

The specific way of determining the time-frequency components uses a short time Fourier transform using a Hanning window  $W(m)$  of an order  $M$  defined by the following equation as one example in this embodiment, but the effectiveness of the invention is not limited to this selection of the window function.

[Equation 1]

$$W(m) = \{1 - \cos[2\pi(m+1)/(M+1)]\}/2 \quad \dots (1)$$

Here,  $m = (0, 1, 2 \dots M-1)$ , and with respect to the real number  $x$ , the symbol  $\cos(x)$  represents a cosine function of  $x$  and the symbol  $\pi$  represents pi.

With respect to the set time intervals  $In$ , the time-frequency components  $Cn(f)$  (where  $f = 0, 1, 2 \dots M-1$ ) is determined by the following equation.

[Equation 2]

$$Cn(f) = \sum_{\{0 \leq m \leq M-1\}} \{x(Tn+m\Delta T)w(m)\exp(-2\pi ifm/(M-1))\} \quad \dots (2)$$

Here, the symbol  $i$  represents an imaginary unit, and with

respect to the complex number  $x$ ,  $\exp(x)$  represents an exponential function of  $x$ . Also, with respect to the sequence  $\{a(m)\}$ , the symbol  $\sum_{0 \leq m \leq M-1} \{a(m)\}$  represents an operation that corresponds the sum  $a(0)+a(1)+\cdots+a(M-1)$  of the sequence.

Below, with respect to the logical expression  $f(x)$  and the sequence  $a(x)$ ,  $\sum_{f(x)} \{a(x)\}$  will represent an operation that corresponds the sum  $a(x_0)+a(x_1)+\cdots+a(x_k)$  (where  $\{x_0, x_1, x_k\}$  is a set of numbers satisfying the logical expression  $f(x)$ ) of the sequence on the set of  $x$  where the logical expression  $f(x)$  becomes the true value.

The knocking detecting means 4 does not require all time-frequency components. Because of the condition that the original ion current sampled values are real numbers, all of the time-frequency components  $C_n(f)$  (where  $\{f = 0, 1, \cdots M-1\}$ ) are not independent. In the time-frequency transforming means 3, the time-frequency components  $C_n(f)$  are determined only with respect to the value of  $f$  necessary to the knocking detecting means 4 that the detection control means 5 determines.

It is commonly known that knocking causes vibrations having as primary components frequencies determined by the shape, pressure, temperature and molecular weight inside the cylinders. Of those frequencies, the frequency where the amplitude experimentally reaches a maximum is taken as a primary frequency  $f_0$ , and the frequencies at both sides thereof where the amplitudes experimentally reach a minimum are taken as  $f^-$  and

$f^+$ . In this embodiment, only the time-frequency components  $Cn(f_0)$ ,  $Cn(f^-)$  and  $Cn(f^+)$  with respect to  $f_0 = 6$ ,  $f^- = 3$  and  $f^+ = 9$  are calculated, but it is also possible to vary this selection in accordance with the running status. Also, the effectiveness of the invention is not limited to these values.

When knocking occurs and vibrations are caused, the absolute value  $|Cn(f_0)|$  of the primary vibration component takes a large value. Below, the symbol  $|x|$  will represent the absolute value of  $x$ . However, it can also take a large value when impulse noise is superposed on the ion current. Thus, in the knocking detecting means 4, the following determination equation is calculated.

[Equation 3]

$$D(n) = (2 \times |Cn(f_0)| - |Cn(f^-)| - |Cn(f^+)|) \quad \dots (3)$$

While this value takes a large positive value with respect to the ion current sampled values when vibration caused by knocking arises, it becomes possible to suppress the influence thereof when the ion current values are configured from impulse noise. However, when the ion currents themselves are amplified by additives, this determination equation is proportional to the ion current intensity coefficient that is the amplification degree thereof. In order to prevent erroneous determination resulting from this influence, the determination equation is divided by a standard factor  $C$  defined by the following equation.

[Equation 4]

$$C = [\sum\{0 \leq f \leq M/2-1\} \{|C_n(f)|^2\}]^{(1/2)} \quad \dots (4)$$

Here, with respect to the complex numbers  $x, y$ , the symbol  $x^y$  represents the function of  $x$  to the power of  $y$ .

In this manner, a determination function  $E(n)$  whose resistance is high with respect to the superposition of impulse noise and changes in the ion current intensity coefficient is obtained by the following equation.

[Equation 5]

$$E(n) = (2 \times |C_n(f_0)| - |C_n(f_-)| - |C_n(f_+)|) / [\sum\{0 \leq f \leq M/2-1\} \{|C_n(f)|^2\}]^{(1/2)} \quad \dots (5)$$

In the present embodiment, the above determination function value is compared to a preset threshold  $Th$ , but the determination function may be determined by a similar function meeting the above-described resolution principle.

Figs. 4A, 4B and 4C show results where it is applied to specific data in this embodiment. The determination function values shown in Fig. 4C are obtained from the ion current shown in Fig. 4A, and knocking can be reliably determined by making the threshold  $Th$  0.1. The change in the intensity of the time-frequency components catches the vibration generated by knocking, the values of the determination function greatly exceed the threshold, and knocking is clearly detected. It should be noted that, although a case is described as an example where  $Th = 0.1$  in this embodiment, the effectiveness of the

invention is not limited to this value.

#### Second Embodiment

Figs. 5A, 5B and 5C are explanatory graphs describing ion current time-frequency transformation results and knocking determination function values in a knocking detection apparatus and detection method according to a second embodiment of the invention. In the first embodiment, the time-frequency components were determined by a short time Fourier transform using a Hanning window function, but in the present embodiment, the window function of equation 6 is used to obtain a Gabor wavelet component.

[Equation 6]

$$w(m) = \exp(-L(m-(M-1)/2)^2) \quad \dots (6)$$

Figs. 5A, 5B and 5C show the results when equation 6 is applied to specific data in this embodiment, and show that the state of the occurrence of knocking greatly exceeds the threshold  $Th = 0.1$  and can be determined. Thus, even in this embodiment, knocking is clearly detected similar to the first embodiment. It should be noted that, although  $L = 800/(M-1)^2$  was used as an example for  $L$  in the above equation 6 in this embodiment, the effectiveness of the invention is not limited to this value.

As described above, the knocking detection apparatus of the invention comprises: spark plugs disposed in cylinders of an internal combustion engine; ion current detecting means for detecting ion currents flowing in the spark plugs;

time-frequency transforming means for setting time intervals allowing one or more overlaps within a time from after ignition by the spark plugs to until its own cylinder or another cylinder next ignites and sampling current values of the ion currents in the respective time intervals to determine the time-frequency components thereof; knocking detecting means for detecting knocking on the basis of the time-frequency components; and detection control means for inputting a running status and controlling the time-frequency transforming means and the knocking detecting means. Thus, the knocking detection apparatus of the invention can precisely grasp the distribution of constantly changing combustion energy and can determine knocking and precisely detect the occurrence timing thereof.

The knocking detection method of the invention includes: ion current detecting means for detecting ion currents using spark plugs disposed in cylinders of an internal combustion engine; time-frequency transforming means for setting time intervals allowing one or more overlaps within a time from after ignition by the spark plugs to until its own cylinder or another cylinder next ignites and sampling current values of the ion currents in the respective time intervals to determine the time-frequency components thereof; knocking detecting means for detecting knocking on the basis of the time-frequency components; and detection control means for controlling the time-frequency transforming means and the knocking detecting

means, wherein the detection of knocking is conducted by the detecting control means inputting a running status of the internal combustion engine and controlling the time-frequency transforming means and the knocking detecting means to determine time-frequency components from sampled values of the ion currents. Thus, the knocking detection method of the invention can detect knocking without mistaken operation with respect to noise belonging to different time intervals, can detect knocking without mistaken operation with respect to fuel where the ion current intensity coefficients are different, and enables control of an internal combustion engine in accordance with the occurrence timing of knocking.